COMPONENT PART NOTICE

THIS PAPER IS A COMPONENT PART OF THE FOLLOWING COMPILATION REPORT:

TITLE: Static Aeroelasticity in Combat Aircraft.

TO ORDER THE COMPLETE COMPILATION REPORT, USE AD-A167 595.

THE COMPONENT PART IS PROVIDED HERE TO ALLOW USERS ACCESS TO INDIVIDUALLY AUTHORED SECTIONS OF PROCEEDING, ANNALS, SYMPOSIA, ETC. HOWEVER, THE COMPONENT SHOULD BE CONSIDERED WITHIN THE CONTEXT OF THE OVERALL COMPILATION REPORT AND NOT AS A STAND-ALONE TECHNICAL REPORT.

THE FOLLOWING COMPONENT PART NUMBERS COMPRISE THE COMPILATION REPORT:

AD#: P005 049 - P005 051 AD#:

AD#: AD#:

AD#: AD#:

DTIC FORM MAR 85 463

OPI: DTIC-TID

STATIC AEROELASTICITY IN THE DESIGN OF MODERN FIGHTERS

E. G. Wilson Jr.
Branch Chief - Technology - Structural Dynamics and Loads
McDonnell Aircraft Company
McDonnell Douglas Corporation
P.O. Box 516, St. Louis, Missouri 63166
USA

Abstract

(30 years)

A review of fighter aircraft development programs over the past three decades indicates a trend of increasing emphasis on the consideration of static aeroelastic effects. While early concerns addressed only the impact on air vehicle structural integrity, current design philosophy recognizes and addresses aeroelasticity as a primary design parameter affecting structural optimization, vehicle aerodynamic stability, control effectiveness, and overall performance. Examples from wind tunnel testing, analytical studies, and operational aircraft applications are presented to justify this emphasis, illustrate current methodology and analysis techniques, and make a case for an integrated approach to the consideration of static aeroelastic effects at all stages of the design process.

Introduction

Y. C. Fung, the author of one of the most prominent texts on the subject, defines aeroelasticity in terms of the "phenomena that reveal the effect of aerodynamic forces on elastic bodies" (Reference 1). Another text, Reference 2, refers to aeroelastic phenomena as "the effects, upon the aerodynamic forces, of changes in the shape of the airframe caused by these same aerodynamic forces." Both of these texts make a distinct differentiation between "dynamic phenomena" and the "static aeroelastic phenomena" which the following discussion will be limited to. More specifically, the topic here is the role of static aeroelasticity in the design of modern fighter aircraft.

Static aeroelastic effects are manifested in the form of changes in the total load or lift on the aircraft, or in changes in the overall distribution of load or lift. These changes affect the structural integrity of the vehicle, its static stability, the effectiveness of various control surfaces, and the overall flight performance. The characteristics and magnitude of these aeroelastic effects are dependent on the aerodynamic shape of the vehicle, the structural orientation, the structural stiffness, and the particular flight condition in terms primarily of Mach number and dynamic pressure.

Historically, the study of aeroelasticity began in the early 1920's. However, serious consideration of aeroelastic effects in the design of fighter aircraft, was probably not given until the late 1940's, when significant advances in aircraft performance provided capability for operation at high subsonic speeds and associated dynamic pressures. As indicated in Figure 1, the emphasis on consideration of aeroelasticity has increased over the past three decades. The early 1950's efforts were characterized by minimal consideration, limited to assessing the possible impact on the vehicle structural integrity as a result of overall changes in the vehicle aerodynamic characteristics. Aeroelastic effects were addressed in structural optimization efforts in the 1960's and serious consideration was being given to the impact on performance, relative to control effectiveness and aerodynamic stability. The '70's saw increased emphasis on structural optimization to enhance performance with the advent of serious aeroelastic tailoring and designed-in structural flexibility. Design philosophy today recognizes aeroelasticity as a primary design parameter with dedicated testing and analyses being considered a necessary and integral segment of the vehicle design process.

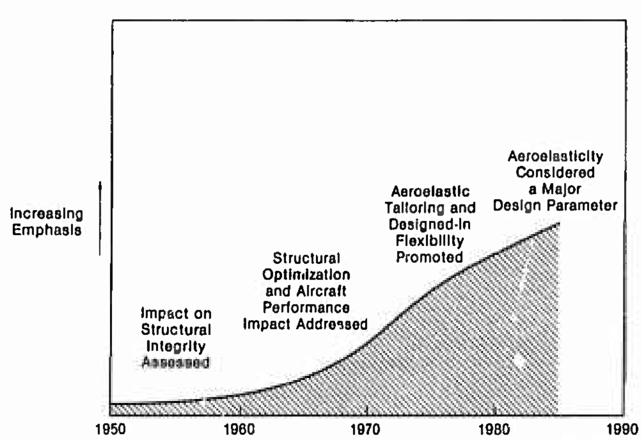


Figure 1. Evolution of Aeroelastic Considerations In Fighter Aircraft Design

Configuration Effects

Lifting surface structural flexibility effects are typically the primary aeroelasticity consideration in fighter aircraft design. Fuselage flexibility is, in general, a secondary consideration. The relatively high density of this structural component, designed to sustain high acceleration levels, and the high structural loadings produced by the close coupled design of most modern configurations, result in high fuselage stiffness. The thin airfoil sections utilized on the lifting surfaces of high speed aircraft, however, lead to inherently flexible structural components with potential aeroelastic sensitivity. Two typical fighter aircraft wing planforms are presented here to illustrate the effects of planform geometry and associated structural orientation on resultant aeroelastic characteristics. The relatively unswept configuration in Figure 2 is basically torsion sensitive. The deflected shape under a subsonic aerodynamic loading exhibits a divergence characteristic as shown in Figure 3. Only overall panel stiffness is considered, and an effective elastic axis, for a conventional structural concept is assumed at 40% of the local chord. The pressure loading and the non-dimensional lift distributions for both the rigid and flexible cases are presented in Figures 4 and 5. The lift distributions illustrate the structural-load-magnification aeroelastic characteristic. Structural optimization of this wing must provide adequate stiffness to insure a divergence speed well in excess of the operational envelope of the aircraft. The swept wing in Figure 6 exhibits bending aeroelastic sensitivity due to the orientation of the main structural torque box. Note the highly swept outer panel reference axis. In Figure 7, the deflected shape of this wing under a maneuvering load, illustrates the swept-axis-bending induced streamwise twist. The transonic loading illustrated in Figure 8 tends to accentuate the aeroelastic relief due to the relatively far aft chordwise center of pressure on the cambered airfoil. The lift loss in the area of the wing tip is apparent in the comparison of rigid and flexible spanwise distributions in Figure 9.

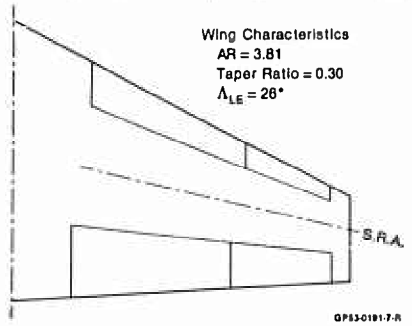


Figure 2. Unswept Wing Configuration

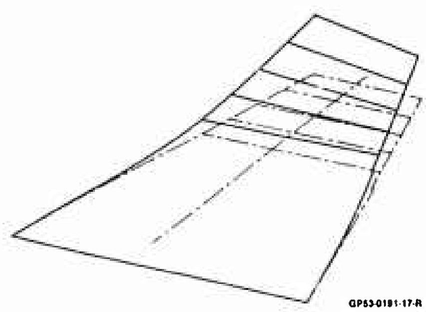


Figure 3. Unswept-Wing Deflection Characteristics

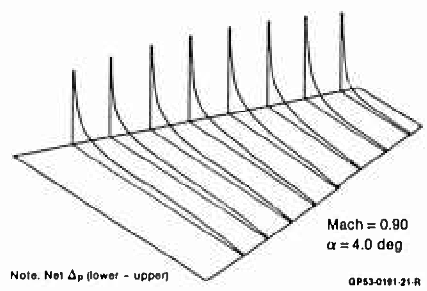


Figure 4. Typical Subsonic Pressure Distribution on an Unswept, Uncambered Wing

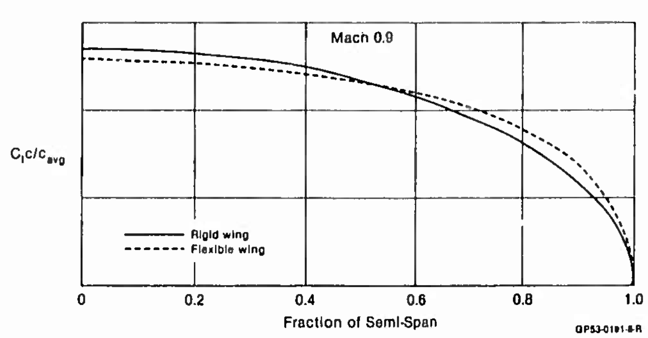


Figure 5. Unswept Wing Nondimensional Spanwise Lift Distribution

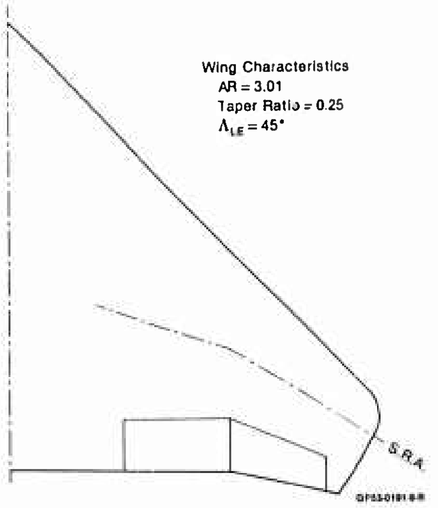


Figure 6. Swept Wing Configuration

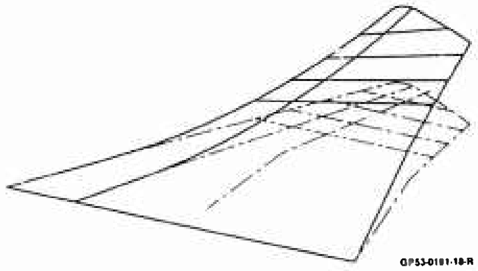


Figure 7. Swept-Wing Deflection Characteristics

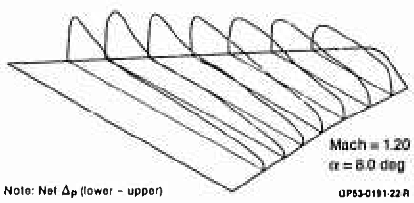


Figure 8. Transonic Pressure Distribution on a Swept Cambered Wing

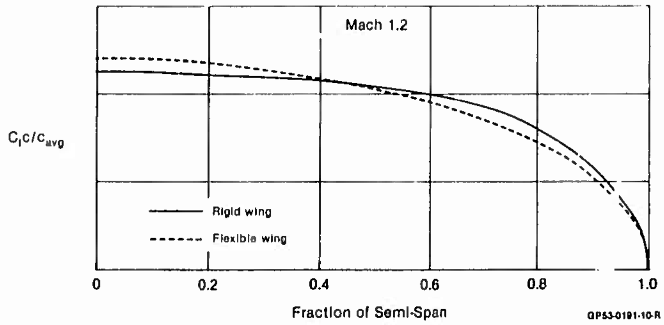


Figure 9. Swept Wing Nondimensional Spanwise Lift Distribution

The data presented above has all been derived by analysis using generally accepted lifting surface aerodynamic codes. Analytical aerodynamics currently provides the foundation for the majority of our aeroelastic design activities and configuration optimization efforts. Two areas of investigation are not being adequately addressed with analytical tools, however. Current state-of-the-art aerodynamic codes do not provide sufficient accuracy to predict either local flow anomalies in the transonic flight regime or the non-linear effects of flow separation observed at elevated angles of attack. The Euler and Navier-Stokes formulations (References 3 and 4) and iterative perturbation techniques (Reference 5) are producing promising results. Advances in computer technology may allow routine use of these complex codes in the future design environment. Wind tunnel testing is currently required, however, to obtain accurate data in these areas.

Wind Tunnel Testing

Figure 10 illustrates a model used in a limited aeroelastic wind tunnel investigation performed in the mid-1960's. The variable sweep configuration is defined in more detail in Figure 11, and the construction technique employed for the flexible wing panels is shown in Figure 12. The welded steel skeleton was packed with polyurethane foam and encased in silicone rubber which provided the appropriate surface contour. The strain gage instrumentation located near the wing root was calibrated to measure panel shear, bending moment, and torsion. Testing was performed at subsonic and supersonic Mach numbers and various dynamic pressures to determine aeroelastic effects on loads and on aircraft stability. Test conditions were duplicated with a set of rigid wing panels to establish a base. An additional objective of the flexible model testing was to obtain correlation data to validate or refine lifting surface aerodynamic codes. Figure 13 illustrates the correlation between predicted variations in total model normal force and wing panel root bending moment with dynamic pressure. Good agreement is shown at this subsonic Mach number and low angles of attack. Figure 14 illustrates the normal force and pitching moment characteristics obtained from the model main balance. Note the unstable break in the rigid model pitching moment and the lack of a dominant break in the flexible model data. The apparent delayed wing tip flow separation on the flexible model was also reflected in the wing bending data. This singular example provides a strong case for aeroelastic wind tunnel model testing. Linear theories would not have predicted the rigid model stability and, with appropriate rigid wind tunnel model data available, linear theory would not provide the appropriate aeroelastic corrections.

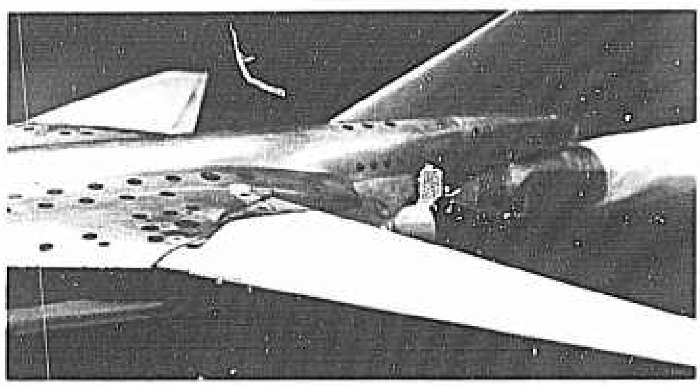


Figure 10. Variable Sweep Flexible Wing Wind Tunnel Model

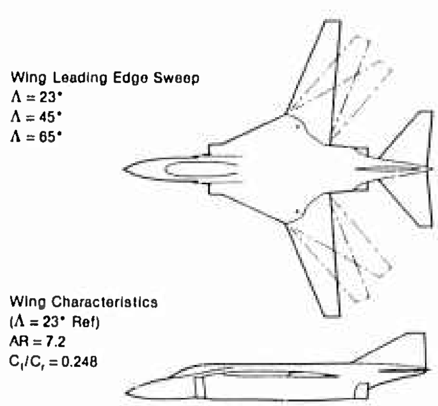
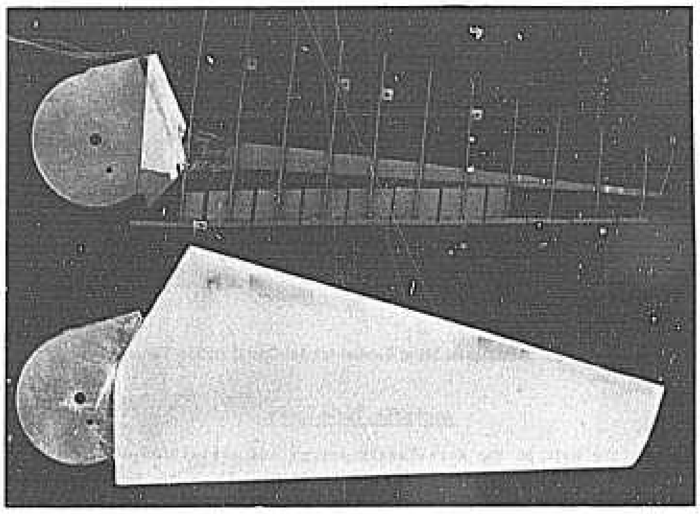
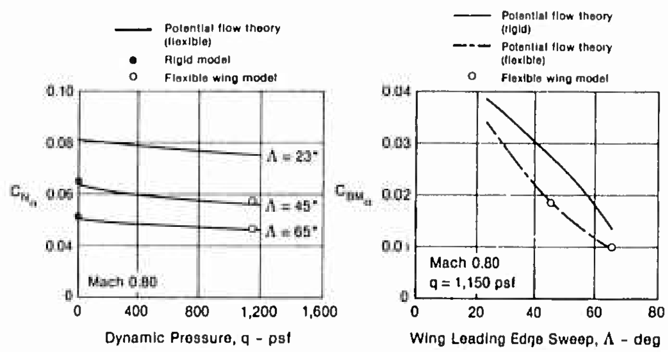


Figure 11. Wind Tunnel Model Configuration



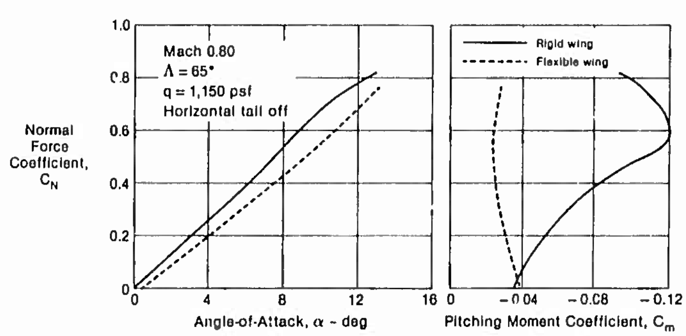
GP53-0191-4-R

Figure 12. Wind Tunnel Model Flexible Wing Panel Construction



GP53-0191-19-R

Figure 13. Effect of Wing Sweep on Lift and Lift Distribution



GP53-0191-3-R

Figure 14. Lift and Pitching Moment Characteristics

Aeroelastic panel construction techniques employed in other test programs are illustrated in Figure 15. Approach (b), with a stiffness scaled beam machined along a predicted elastic axis, and load isolation cuts forward and aft of the beam, has proved to be most successful. Approach (a), with a foam filled steel skeleton and fiberglass covering was an attempt to reduce the mass and improve the model flutter margin. The minor improvement achieved in testing range did not justify the added complexity of the model. Approach (c) employs a multi-layer fiberglass layup and may be appropriate for small surfaces. However, stiffness distribution control is difficult with this type of construction.

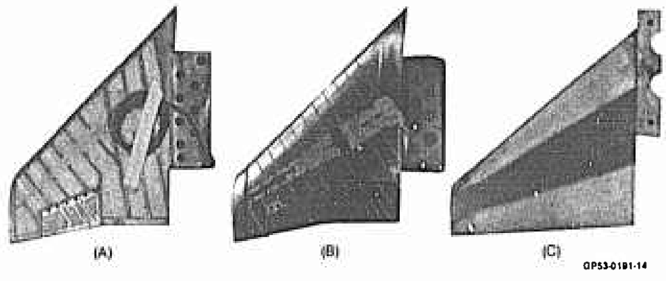


Figure 15. Aeroelastic Wind Tunnel Model Construction Techniques

Analysis Techniques

As mentioned above, the bulk of the aeroelastic design and evaluation effort is supported by analytical methods. Recent improvements in the various aerodynamic theories and panel aerodynamics computer codes have provided a source for an appropriate loading definition throughout a large portion of the operating envelopes of current and projected future fighter aircraft. The other major component of the aeroelastic analysis is the structural stiffness model. Current structural design methodology employs the finite element modeling techniques of computer programs such as NASTRAN. The optimization capabilities and inherent comprehensive accuracy of these techniques have resulted in a dependence on their utilization in virtually all phases of the design process. A by-product of the finite element internal loads solution is an accurate and highly detailed structural stiffness definition which may be used directly in the aeroelastic analysis. Figure 16 is a point-line representation of the major elements in a typical wing finite element model. The bold points indicate locations at which influence coefficients would be obtained to provide a comprehensive stiffness representation of the panel. An aeroelastic analysis utilizing a representation of this type and an appropriate aerodynamic theory wil' yield not only a detailed definition of the net loading, but also a complete deflection pattern for the loaded structure as illustrated in Figure 17.

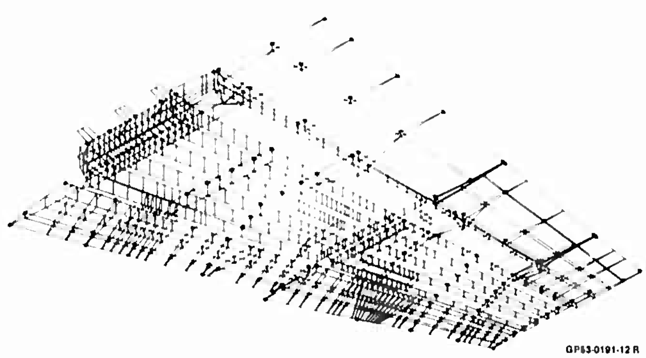


Figure 16. Wing Finite Element Structural Model

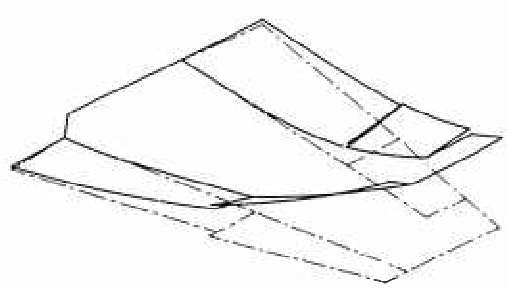


Figure 17. Deflected Shape of Wing Structural Model Under a Typical Maneuvering Loading

An evaluation of the aeroelastic implications of minor structural concept changes, or parametric tradeoffs on a baseline configuration, may require utilization of a simplified, more versatile, stiffness representation of the structure. An effective beam representation of the total panel stiffness is generally applicable and appropriate for these needs and also satisfies the requirement for defining wind tunnel model construction. Model strength and scale factors typically dictate a beam stiffness approach to the representation of the full scale surface flexibility.

Figure 18 presents the results of a control effectiveness study performed on a desk top computer utilizing an effective beam stiffness model. The swept wing configuration of Figure 6 exhibits torsional aeroelastic sensitivity, as well as primary bending sensitivity, when loaded by a deflected trailing edge aileron. At high dynamic pressure flight conditions, the flexible wing loading produces the zero net aileron effectiveness, or actual aileron reversal, as illustrated in Figure 18. Structural stiffness parametric studies are easily performed on the simplified beam model by factoring the effective bending stiffness (EI) or torsional stiffness (GJ) to produce the results shown in Figure 19.

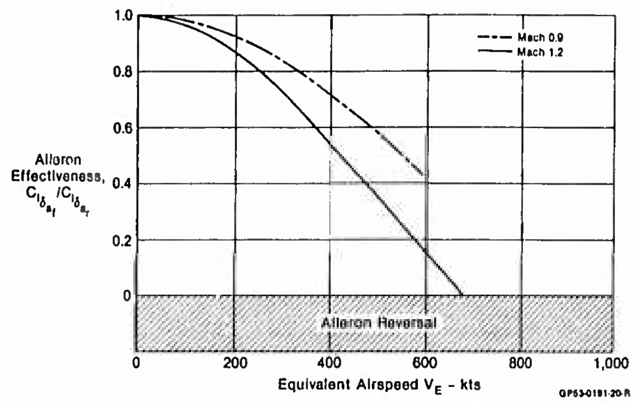


Figure 18. Typical Aileron Effectiveness Trends

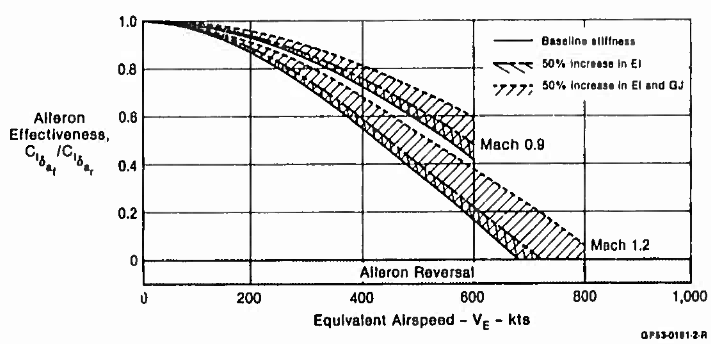


Figure 19. Parametric Study of Aileron Effectiveness vs Stiffness

Operational Aircraft Applications

A fully integrated design environment, in which aeroelastic implications are considered at all stages of the design evolution, provides the capacity for implementing aeroelasticity-dependent design features to enhance the overall performance of the evolving configuration. Early identification of an aileron effectiveness deficiency in the configuration shown in Figure 2, for example, could lead to incorporation of an aeroelastic device to enhance the roll power. The leading edge flaps of this wing are designed to improve the low speed, high lift, or high angle of attack characteristics of the thin, sharp edged airfoil. Deflection of the flaps at subsonic Mach numbers on a rigid wing produces the characteristic chordwise pressure profile shown in Figure 20. The net loading effect is to produce zero wing lift, but a large leading-edge-up wing torque. Aeroelastically, a significant wing lift is generated as the wing is twisted by the applied torque. A large aircraft rolling moment is generated by deflecting the flaps differentially, left/right. This active aeroelastic performance enhancement device is currently utilized on the F-18 aircraft.

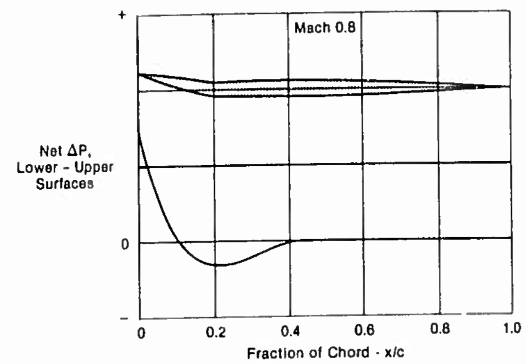


Figure 20. Chordwise Pressure Loading Due to Deflected Leading Edge Flap

The swept wing planform of Figure 6 is implemented on the F-15 aircraft with conical wing camber to enhance the lift characteristics at the primary maneuvering design point. At high transonic Mach numbers and high maneuvering angles of attack, the chordwise load distribution near the wing tip is nearly uniform as illustrated by the rigid model pressure data in Figure 21. High speed roll control on this aircraft is principally achieved from differential deflection of the horizontal tail panels. Due to the aeroelastic bending sensitivity of the wing, the ailerons are relatively ineffective at these conditions. Considering these facts, and the fairly low aileron hinge moments required for subsonic maneuvering, the hinge moment capability of the aileron was judiciously chosen to allow the surface to "float," or unload in high speed, high angle of attack maneuvers. This passive aeroelastic device effectively reduces critical structural loads in the outer panel of the F-15 wing.

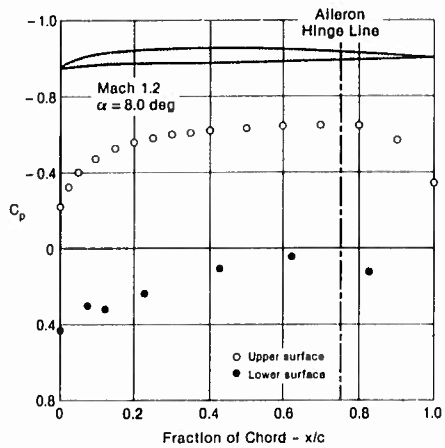


Figure 21. Chordwise Pressure Distribution Due to Symmetric, High Load Maneuvering

Summary

Consideration of static aeroelasticity in the design of fighter aircraft has evolved over the past three decades from a defensive posture to a positive approach of integrated analyses and designed-in structural flexibility to achieve enhanced performance. This positive approach requires coordinated efforts in several technology areas including analytical aerodynamics, wind tunnel testing, structural modeling, aircraft performance appraisal, configuration design, and systems integration. Both active and passive aeroelastic design features have been incorporated in current operational fighter aircraft. Advances in materials, structural concepts, and controls technology are providing expanded opportunities for implementation in the next generation of aircraft.

References

1. Fung, Y. C.: An Introduction to the Theory of Aeroelasticity, Dover Publications, 1969.
2. Etkin, B.: Dynamics of Flight - Stability and Control, Wiley & Sons, 1959.
3. Verhoff, A. and O'Neill, P. S.: A Natural Formulation for Numerical Solution of the Euler Equations, AIAA-84-0163, 1984.
4. Cosner, R. R.: Relaxation Solution for Viscous Transonic Flow about Fighter-Type Forebodies and Afterbodies, AIAA-82-0252, 1982.
5. Gilmer, B. R. and Bristow, D. R.: Analysis of Stalled Airfoils by Simultaneous Perturbations to Viscous and Inviscid Equations, AIAA-81-1239R, 1981.